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Quarkonium in Hot Medium

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1 Introduction

There has been considerable interest in studying quarkonia in hot medium since the famous paper by Matsui and Satz [1] was published. It has been argued that color screening in a deconfined QCD medium will suppress the existence of quarkonium states, signaling the formation of a quark-gluon plasma in heavy ion collisions. Although this idea has been proposed long time ago, first principle QCD calculations, which try to go beyond qualitative arguments have been performed only recently. Such calculations include: lattice QCD determinations of quarkonium correlators [2–5], potential model calculations of the quarkonium spectral functions with potentials based on lattice QCD [6–12], as well as effective field theory approaches that justify potential models and uncover new medium effects [13–15]. Furthermore, better understanding on how to model quarkonium production in media created in heavy ion collisions has been achieved. These advancements allow for the disentanglement of what are the cold- and hot-nuclear matter effects on the quarkonium states and their suppression, and is crucial for the interpretation of data obtained in heavy ion collisions.

2 Color screening and deconfinement

At high temperatures strongly interacting matter undergoes a deconfining transition to a new state usually referred to as quark-gluon plasma (QGP). This transition is triggered by a rapid increase of the energy density and entropy density, as well as the disappearance of hadronic states (for a recent review see [16]). According to current lattice calculations deconfinement (at zero net baryon density) happens at temperatures $(170 - 195)$ MeV [16]. The QGP is characterized by color screening: the range of interaction between heavy quarks becomes inversely proportional to the temperature. Thus at sufficiently high temperature binding between a heavy quark (c or b) and its antiquark is impossible.

Color screening is studied on the lattice by calculating the spatial correlation function of a static quark and anti-quark in the color singlet state, which propagates in Euclidean time from $\tau = 0$ to $\tau = 1/T$, where T is the temperature (see [18] for a recent review). The logarithm of this correlation function is called the singlet free energy and is shown in Fig. 1. As expected, in the zero temperature limit the singlet free energy coincides with the zero temperature potential. Fig. 1 also illustrates that at sufficiently short distances the singlet free energy is temperature independent and coincides with the zero temperature potential. This range of interaction decreases with increasing temperatures. For temperatures above the transition temperature T_c the heavy quark interaction range becomes comparable to the size of charmonium. Based on this general observation one would expect that charmonium states, and excited bottomonium states, do not exist just above the deconfinement transition (note that in the literature this is often termed as dissociation or melting).

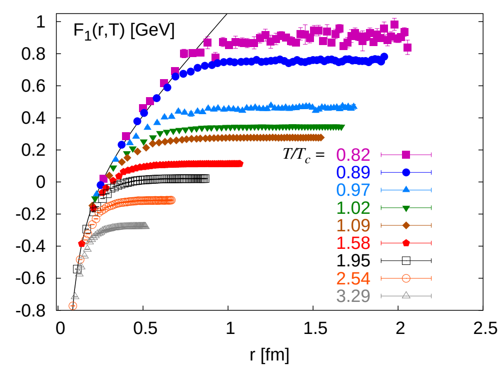

Fig. 1. Heavy quark singlet free energy versus quark separation calculated in 2+1 flavor QCD on $16^3 \times 4$ lattices for different temperatures [17].

3 Quarkonium spectral functions

In-medium quarkonium properties, as well as their dissolution at high temperatures is encoded in the corresponding spectral functions. Spectral functions are defined as the imaginary part of the retarded correlation function of quarkonium operators. Bound states show up as peaks in the spectral functions. With increasing temperatures the peaks broaden and eventually disappear. The disappearance of a peak signals the melting of the given quarkonium state.

In lattice QCD one calculates meson correlation functions in Euclidean time $G(\tau, T)$. These are related to the spectral functions $\sigma(\omega, T)$ via

$$G(\tau, T) = \int_0^\infty d\omega \sigma(\omega, T) \frac{\cosh(\omega(\tau - 1/(2T)))}{\sinh(\omega/(2T))} . \qquad (1)$$

Having very detailed information on $G(\tau, T)$ could allow the reconstruction of of the spectral function from the lattice data. In practice, however, this turns out to be very difficult task, because the time extent is limited as $1/T$ (see discussion in Ref. [4] and references therein).

One can calculate quarkonium spectral functions in potential models using the singlet free energy of Fig. 1, or different lattice-based potentials obtained from the singlet free energy as an input [11,12] (and for a review see [19]). The results of the calculations (in quenched QCD) are shown in Fig. 2 for S-wave charmonium (upper panel) and bottomonium (lower panel) spectral functions [11]. One can see that all charmonium states are dissolved in the deconfined phase, while the bottomonium ground state may persist up to temperature of about $2T_c$. From the calculated spectral functions, using equation (1), one can predict the temperature dependence of the Euclidean correlators. Somewhat surprisingly, Euclidean correlation functions show very little temperature dependence, irrespective, whether a state is there (such as the Υ) or not (such as the J/ψ). Note also, that correlators from potential models are in accordance with the lattice calculations (see insets in Fig. 2). Originally, the small temperature dependence of the correlators was considered as an evidence for survival of different quarkonium states [3]. It is now clear that this conclusion was premature.

In the spectral functions we see a large enhancement in the threshold region, shown in Fig. 2 in comparison to the free spectral function (dotted lines). This threshold enhancement compensates for the absence of bound states and leads to Euclidean correlation functions which show only very small temperature dependence [11]. It further indicates strong residual correlations between the quark and anti-quark even in absence of bound states. Similar analysis was done for the P-wave charmonium and bottomonium spectral functions [11,12]. From the analysis of the spectral functions one can provide an upper bound for the dissociation temperatures, i.e. the temperatures above which no bound states peaks can be seen in the spectral function, temperatures above which bound state formation is suppressed. Conservative upper limit dissociation temperatures for the different quarkonium states from a full QCD calculation [12] are given in Table 1.

The application of potential models can be justified using an effective field theory approach. For heavy quarks the existence of different energy scales related to the heavy quark mass m, the inverse size mv (v is the heavy quark

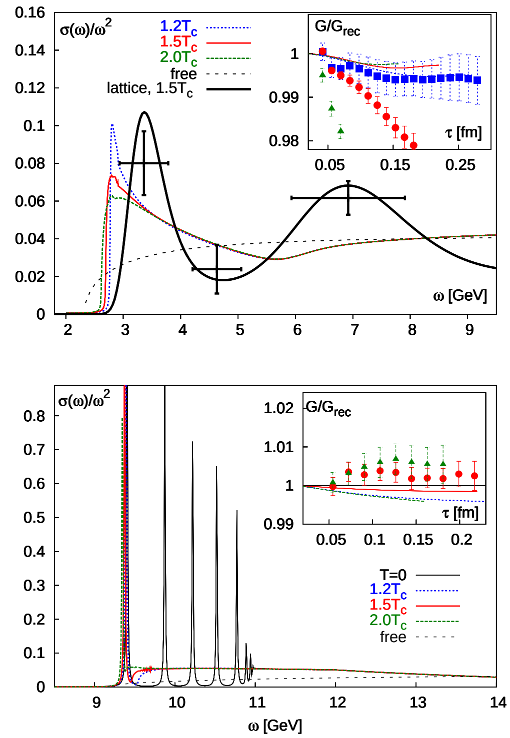

Fig. 2. S-wave charmonium (upper) and bottomonium (lower) spectral functions calculated in potential model [11]. Insets: correlators compared to lattice data.

state	χ_c	ψ'	$J\psi$	Υ'	χ_b	Υ
T_{diss}	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

Table 1. *Upper bounds* for the dissociation temperatures [12].

velocity), and the binding energy mv^2 allows to construct a sequence of effective theories at zero temperature. The effective theory which emerges after integrating out the scale m and mv^2 is the pNRQCD, which delivers the potential model at $T = 0$. It is possible to extend this approach to finite temperature, where additional scales are present. These scales are are the temperature T, the Debye mass $m_D \sim gT$, and the magnetic scale g^2T. In the weak coupling regime, where $g \ll 1$ these scales are well separated. Depending on how these thermal scales are related to the zero temperature scales, the different hierarchies allow one to derive different effective theories for quarkonium bound states at finite temperature [15]. In this weak coupling QCD approach thermal corrections to the potential are obtained when the temperature is larger than the binding energy. An important common result of these effective theories is that the potential acquires an imaginary part. The imaginary part of the potential leads to the smearing of the bound state peaks in the quarkonium spectral function, leading to their dissolution, even before the onset of the exponential Debye-screening of the real part of the potential (see e.g. discussion in [14]).

Most recently, first attempts to address the effects of the possible anisotropy of the medium on quarkonium states have been considered both for the real part of the potential [20] and its effects on the binding of the states [21], as well as for the imaginary part of the potential [22,23]. As a consequence, the polarization of the P-states due to the medium anisotropy has been predicted, with a sizable 30% effect for the χ_b state [21]. The relevance of these studies should be explored further, since a weak medium anisotropy may be related to the shear viscosity of the medium [24], and thus could allow for testing the properties of the medium produced in heavy ion collisions.

4 Dynamical models for quarkonium production

Knowing the quarkonium spectral functions in equilibrium QCD is necessary, but alone is not sufficient to predict their production in heavy ion collisions. This is because unlike the light degrees of freedom, heavy quarks are fully thermalized in the course of heavy ion collisions. Therefore, it is non-trivial to relate the finite temperature quarkonium spectral functions to quarkonium production rates in heavy ion collisions without further model assumptions. The bridge between the two is provided by dynamical models for the matter produced in heavy ion collisions. Some of the simplistic models currently available are based on statistical recombination [25], or statistical recombination and dissociation rates [26], or a sequential melting scenario [27]. Here we highlight a more recent model, which tries to make closer contacts to QCD and experimental observations in heavy ion collisions [30].

The bulk evolution of the matter produced in heavy ion collisions is well modeled by hydrodynamics (see [28] for a recent review). Due to its large mass the interaction of a heavy quark with the medium can be modeled by Langevin dynamics [29]. Such approach successfully describes the anisotropic flow of charm quarks observed at RHIC [29]. We learned from potential models that in the absence of bound states the quark-antiquark pairs are correlated in space [11,12]. This correlation can be modeled classically, using Langevin dynamics which includes a drag force and a random force on the heavy quark (antiquark) from the medium, as well as the forces acting between the quark and anti-quark (described by the potential). It was recently shown, that such modeling of the expanding medium by ideal hydrodynamics and of the correlated quark anti-quark pair dynamics by Langevin equation can describe the RHIC data on charmonium suppression quite well [30]. In particular, this model can explain why despite the fact that a deconfined medium is created at RHIC, we see only $40-50\%$ suppression in the charmonium yield. The attractive potential and the finite lifetime of the system prevents some of the quarks and antiquarks to get completely uncorrelated [30]. Once the system cools down sufficiently, these residual correlations make it possible for the quark and antiquark to form a bound state.

The above approach, since it neglects quantum effects, is applicable only if there are no bound states, as it is likely to be the case for the J/ψ. If heavy quark bound states are present, as it is likely to be the case for the ground state bottomonium Υ, the thermal dissociation rate will be the most relevant quantity for understanding the quarkonium yield. It is expected, that the interaction of a quarkonium with the medium (being a color singlet state) is much smaller than that of the heavy quarks. Thus to first approximation the effect of the medium will only lead to quarkonium dissociation.

5 Concluding remarks

Potential model calculations based on lattice QCD, as well as resummed perturbative QCD calculations indicate that all charmonium states and excited bottomonium states dissolve in the deconfined medium. This leads to the reduction of the quarkonium production yield in heavy ion collisions compared to the binary-scaled proton-proton collisions. Due to possible recombination effects, however, the yield will not be zero.

One of the great opportunities of the upcoming LHC and RHIC2 heavy ion experiments is the measurements of the bottomonium yield. From theoretical perspective bottomonium is a very interesting and clear probe for at least two reasons: First, the effective field theory approach which provides a link to first principle QCD, is most applicable for bottomonium. This is because of a better separation of the bound state scales and because of the obtained higher dissociation temperatures. Second, due to the significantly heavier bottom quark mass the role of recombination will be different. Thus, bottomonium is a good probe of the existing dynamical models as well.

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